Date: January 6, 2017

EIC Detector R&D Progress Report

Project ID: eRD17
Project Name: DPMJetHybrid 2.0: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing / Saturation Regime
Period Reported: from July, 2016 to December, 2016
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Abstract

The purpose of this project is to upgrade the eA DIS event generator BeAGLE (formerly called DPMJetHybrid) to include some key nuclear shadowing / parton saturation effects that are currently missing in the suite of eA event generators available for physics simulations. These event generators, partly supported by previous EIC R&D funding, have been essential in establishing detector requirements for various physics measurements. However, the particle production model in the forward region for eA (along the ion direction) needs improvement in order to clarify those requirements for measurements at either eRHIC or JLEIC. We plan to add a flexible model for intrinsic k_T and multi-nucleon k_T-recoil sharing for eA collisions. This model will automatically factor in improved information as we include updated nuclear PDFs from RHIC or the LHC. In order to test and shakedown the model, we plan to use it to study the impact of forward detectors on two important topics in eA: centrality measures and correlations between forward particles and particles from the hard scattering.

Past

<u>What was planned for this period?</u>

We had expected to implement multi-nucleon shadowing and have a quick look at the physics impact before focusing on further improvements to the BeAGLE code. A beta release of the code was planned for the end of January.

<u>What was achieved?</u>

The simulation code was renamed from DPMJetHybrid 2.0 to **BeAGLE** (**B**enchmark **eA** **G**enerator for **LE**ptoproduction) and the beta version is already installed and available at BNL. It is expected to be installed at JLAB later this month. It already has a substantial number of improvements over the old DIS eA codes and more are planned. The chart below compares the old choices: DPMJet, Pythia(EIC), and DPMJetHybrid, with the current and planned state of BeAGLE.

Feature added or error corrected	DPMJet	Pythia (EIC)	DPMJet-Hybrid	BeAGLE β	BeAGLE (planned)
1. Hard processes correct.	NO	YES	YES	YES	YES
2. Tuned to ZEUS ep→p+X data	NO	YES	YES	YES	YES
3. IntraNuclear Cascade	YES	NO	YES	YES	YES
4. Nuclear evaporation/breakup	YES	NO	YES	YES	YES
5. Multinucleon shadowing available.	YES	NO	NO	YES	YES
6. Correct nucleon remnant (n/p)	YES	NO	NO	YES	YES
7. Correct eA target rest frame	NO	NO	NO	YES	YES
8. Tuned to E665 μPb→n+X data	YES	N/A	YES	YES/NO	YES
9. Shadowing coherence length	YES	N/A	NO	NO	YES
10. Partial shadowing effect	NO	NO	NO	NO	YES
11. Process-specific A dependence	NO	NO	NO	NO	YES
12. Tuned to more E665 μA data	NO	N/A	NO	NO	YES
13. FS p_F for hard process correct	???	NO	NO	NO	YES
14. Quenching correctly applied	N/A	N/A	NO	???	YES*
15. IS p_F for hard process correct	???	NO	NO	NO	NO

* - The correct integration and testing of the quenching package, PyQM, in BeAGLE will be carried out in the JLAB LDRD, as discussed below, in collaboration with the PyQM authors, and is not technically part of eRD17.

It should be noted that not all of the lines in the table are of equal importance. In particular, the correct description of the hard collision at high values of Q^2 (jets, QCD radiation etc.) is essential for EIC physics, which is why the original DPMJet needed to be improved to start with.

All of the codes discussed here are installed at BNL in the "PACKAGES" area: /afs/rhic/eic/PACKAGES/. DPMJet refers to DPMJet 3.0-5. Pythia(EIC) refers to the PYTHIA version 6.4.28 installed at BNL (pythiaeRHIC), which has some modifications to better handle the low Q^2 region. DPMJetHybrid refers to the version which preceded the start of eRD17 in October 2015. The BeAGLE (β) refers to the currently released version of BeAGLE while BeAGLE (final) refers to the planned version to be released at the end of the project.

The first column refers to desired features and/or errors to be corrected. The next three columns show the state of affairs before eRD17 began. DPMJet, using GVMD (Generalized Vector Meson Dominance) to describe eA collisions was successful at describing many nuclear effects, including shadowing and multinucleon collisions, intranuclear cascading, as well as nuclear evaporation and breakup. However, it was found to have completely incorrect behavior for $Q^2 >> M^2_N$. Pythia, on the other hand, described well the ep LO-DIS events as well as the $O(\alpha_s)$ corrections at high Q^2 and also the transition to GVMD at lower Q^2. When it came to nuclear effects, however, apart from the trivial parton distribution function change, Pythia was "not even wrong". It simply didn't try to describe any of these nuclear effects. DPMJetHybrid was a fairly successful attempt to combine the best features of Pythia and DPMJet while adding in the quenching code PyQM[1-3], but several compromises were made in order to combine these programs. In particular, DPMJetHybrid (1.0), unlike DPMJet, did not allow multiple nucleons to participate in an event; always used a proton target beam remnant, even when the struck nucleon was a neutron (failing therefore to conserve charge); and ignored the Fermi momentum of the struck nucleon (failing therefore to conserve momentum).

The final two columns, highlighted in yellow, show the status of the current beta-release of BeAGLE (labeled β) as well as the planned status at the end of eRD17 (end of FY2017). The eRD17 project was proposed in order to improve DPMJetHybrid, with an emphasis on the shadowing region effects. In addition to the known problems, we discovered some minor technical bugs as well as some conceptual problems along the way. The improvements made already will be discussed in detail in the current section while the remaining, planned improvements will be discussed in the next section.

The first four rows of the table refer to features of DPMJetHybrid that have been preserved in BeAGLE, including the work that Aschenauer and Baker did in tuning intrinsic k_T for Pythia. Row 5, "multinucleon shadowing available," represents the achievement of a major goal of eRD17. As described in previous reports to the committee, when this feature is switched on, BeAGLE uses the shadowing inherent in the nuclear PDF (parton distribution function) to infer an effective hadronic cross-section for the γ^* allowing a

Glauber simulation of γ*A (similar to pA). When the number of collisions (N_{coll}) is >1, one of the struck nucleons is chosen to undergo a Pythia hard interaction while the others undergo an elastic collision with the leading parton with p_T characteristic of intrinsic k_T. When the multinucleon shadowing feature is turned off, or for x>0.1 in any case, BeAGLE reverts to the single-nucleon interaction mode as used by DPMJetHybrid. The comparison between BeAGLE and the old DPMJET can be seen in Figure 1. In both cases, N_{part} (=N_{coll} for eA) is usually 1, but can be larger in some cases.

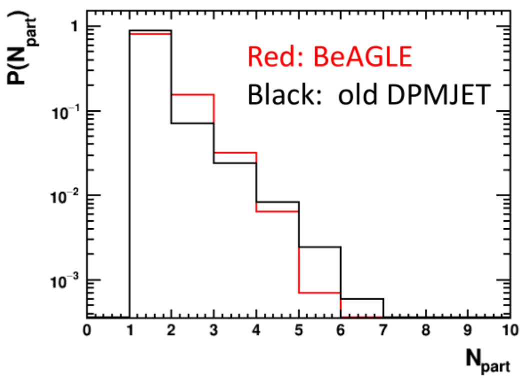

Figure 1. Distribution of the number of participating nucleons in the initial γ*A collision before intra-nuclear cascading for eAu collisons at 10x100.

Row 6, the "correct nucleon remnant (n/p)" refers to a "feature" of pythiaeRHIC that was carried over into DPMJetHybrid. The internal Pythia collision is chosen to be a proton, although the correct nPDF is used rather than the proton PDF. Therefore the struck parton and hard interaction chosen have the appropriate behavior in the current jet direction. However, the target remnant is always that of a proton. In the case of DPMJetHybrid, this leads to an error ~60% of the time when a neutron from the simulated Glauber nucleus is replaced with the results of an ep collision, leading to charge-non-conservation and an incorrect correlation between the struck parton flavor and the nucleon beam jet remnant flavor. This has been fixed in BeAGLE.

Row 7 is caused by a conceptual challenge for eA colliders that does not apply to previous, fixed target, eA collisions. It arises because nuclei have binding energy, with a mass deficit of about 0.8% for Au. The conventional approach has been to assume that the struck nucleon in eA DIS has the mass of a free nucleon while the spectator nucleons might be more complicated. In the case of Pythia, the spectator nucleons are simply ignored, while for DPMJet and DPMJetHybrid, they are also treated as nucleons with the standard mass, but sitting in a potential in the target rest frame which accounts for the mass deficit. The challenge comes when you start boosting the particles to look at them in different frames. Then the picture of the spectators becomes complicated and model-dependent.

One thing however, is clear and model-independent. The boost between the collider lab frame and the target rest frame is well-defined and is based on a Lorentz boost of $-y_A$ where y_A refers to the rapidity of the physical beam. For a gold beam with momentum 19700 GeV (commonly referred to as 100 GeV/nucleon), this leads to a rapidity of $y_A=\sinh^{-1}(p_z/M)=5.3695$. The key point is that a nucleon at rest in the nuclear target rest frame will have the *same* rapidity as the beam in the lab frame, while all 3 programs, pre-BeAGLE, assume that the struck nucleon has 1/A times the momentum of the beam (100 GeV in our example). For an on-mass-shell proton, 100 GeV leads to a rapidity of y_p=5.2912 and in that case the "target rest frame" of the nucleon and nucleus would not be the same. In BeAGLE, we treat the struck nucleon as having the same rapidity as the beam, leading to lab p_Z=100.74 GeV for a struck proton and 100.88 GeV for a neutron.

In order to keep the spectator model as simple as possible, we ONLY consider spectators in the (nuclear) target rest frame, where they are on mass shell, have a small (Fermi) momentum, and experience a mean-field potential. Only the final state particles which have escaped (and had their momentum modified by) the potential are eligible to be boosted to the lab frame.

Line 8 in the chart represents a work in progress. As reported in the status report/proposal from June 2016, we have tuned DPMJetHybrid to the E665 evaporation neutron ePb data and this tune then applies also to BeAGLE with multi-nucleon shadowing turned off. Tuning the BeAGLE multi-nucleon result will take more effort as discussed below in the next section.

As mentioned above, the implementation of multi-nucleon shadowing in BeAGLE represents the achievement of a major goal of eRD17. The remainder of project is primarily concerned with improving the details of the model and testing it on some physics topics.

<u>What was not achieved, why not, and what will be done to correct?</u>
The quick look at the physics plots was not as meaningful as hoped since, as will be discussed below, the extra BeAGLE collisions are implemented in a way which appears to overexcite the nucleus causing it to break up. We don't believe that this is physical, but it will need to be fixed, and the results tuned to E665 data, before the physics plots will be useful. Also, we spent some time dealing with the other issues mentioned above which weren't originally anticipated.

We don't expect this to cause a major delay since we planned to improve the model anyway. Also, we originally expected Zheng to be at BNL in person in Fall 2016, but that visit has moved (due to visa delays) to Spring 2017, which should allow us to catch up due to increased efficiency. This schedule is actually better for eRD17 than the original one since Baker was able to finish a lot of code implementation before Zheng arrived to start running the simulations in earnest.

Future

<u>What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?</u>

Turning on the multinucleon feature of BeAGLE spoils the agreement with the E665 e+Pb evaporation neutron data. The shadowing creates a correlation between N_{coll} and ν leading to a prediction of increasing N_n with ν in contrast to the data. Increasing the formation time parameter τ_0 even higher than its already large value of 9.0 fm/c doesn't improve the agreement. A comparison between BeAGLE and DPMJet, see Figure 2 shows that our implementation in

BeAGLE has caused the extra collisions (after the Pythia one) to generate way to much excitation energy in the nucleus. Note the change in the y-axis scale between the two plots. This difference may be because we don't give the nucleus a chance to recapture the recoiling nucleons and therefore force it to generate more holes in the nucleus than it should.

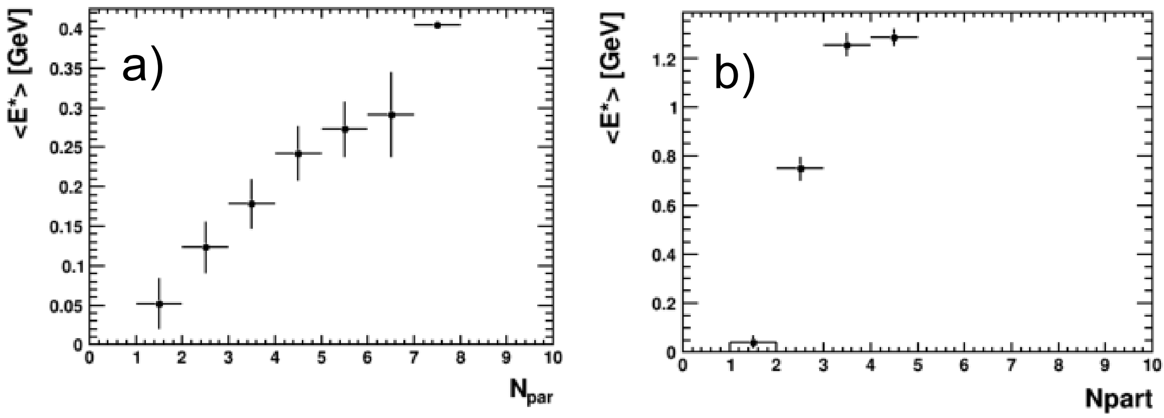

Figure 2. Average nuclear excitation energy of the nuclear remnant in a 10x100 GeV eAu collision as a function of the number of participating nucleons for a) DPMJet and b) BeAGLE.

In general, the first, simplest, version of multinucleon shadowing as implemented in BeAGLE has the following features, all of which can be changed to improve the agreement with the data:

- The nPDF is EPS09-LO, which has large uncertainties. Less shadowing would improve the agreement.
- We assume that the entire nuclear modification for x<0.1 is due to multi-nucleon shadowing, with no room for bound nucleons to be different from free nucleons in terms of parton content.
- When $N_{coll}>1$, we apply a substantial p_T recoil (2d gaussian w 2d-rms of 0.32 GeV) to the struck nucleons that were not selected for Pythia interaction.
- We assume that all recoiling nucleons escape the nucleus and leave a hole without giving the potential a chance to recapture them.
- We use an infinite coherence length rather than a finite one ($\lambda \sim 1/2Mx$).
- The ratio of diffractive to deep inelastic events as a function of A has not been tuned to the data.

The finite coherence length was in DPMJet, but was lost in going to DPMJetHybrid and BeAGLE (line 9). This is unlikely to make a big difference in the agreement with the data, but we plan to add it. The capabilities in lines 10-11 will directly address our ability to tune to the data. Line 10 would allow us to choose an option intermediate to the two extremes currently available in BeAGLE: 1) no multi-nucleon effect vs. 2) all shadowing due to multi-nucleon scattering. Line 11, which would allow for the increase in the ratio of diffractive/DIS cross-sections with A and with the amount of shadowing. It should be remembered that the E665 trigger and event selection typically does not distinguish between DIS and diffractive events. At the time, it was not expected that diffraction would play such an important role in high energy ep and eA collisions, until ZEUS and H1 discovered otherwise. The typical E665 event selection just had a range of Q^2 and ν and then removed some events based on the EM calorimeter. The calorimeter cuts typically removed most of the (QED) radiative events and also some of the simpler diffractive events where the $x_F>0$ was just a scattered ρ^0. After the discovery at HERA of "large rapidity gap" (LRG) events, E665 showed [4] that the "grey track" multiplicity (from IntraNuclear Cascades) was actually *lower* in the low x shadowing region than in the non-shadowing region, contrary to expectations at the time. They further showed that this was caused by an increase in the fraction of LRG events which showed less activity in the target remnant jet than SRG (small rapidity gap) events. It is possible that a similar effect is masking the expected impact of shadowing on the number of evaporation neutrons. We can investigate this by allowing the diffractive events to increase with shadowing (line 11) and by tuning to the E665 streamer chamber "grey track" and overall track multiplicity data (line 12). In the long run, the idea is to have the capability to simulate these effects in BeAGLE and have the *much* better EIC data to allow us to understand what is actually happening.

Finally there are some technical points to consider. In the current version of BeAGLE, as well as in DPMJetHybrid and Pythia, we ignore the Fermi momentum of the nucleon involved in the Pythia eN collision. Naïvely, that should be a small effect, but not necessarily in practice. If we boost from the nuclear target rest frame to a frame with a large boost parameter γ, such as the lab frame or the hadronic center-of-mass frame, the relative change in the longitudinal momentum in the direction of the boost is ~ p_F/M_N which can easily be 10-20%. Ignoring this effect can lead to a substantial momentum non-conservation in the final state. For the final version of BeAGLE, we plan to boost the Pythia eN reaction products to reinstate this momentum (line 13).

A more complicated issue (line 15), fraught with conceptual challenges, would be to apply the Fermi momentum correctly before the Pythia eN collision and change the effective s_{eN} event by event. This would require keeping separate track of the target rest frame of the nucleon and the nucleus. More importantly, it would require keeping separate track of the values of ν, x, W^2 etc. inferred using the nuclear target rest frame vs. the actual nucleonic target rest frame values (Note: Q^2 is unaffected). In addition, since the nPDFs are *defined* using the assumption of $TRF_A = TRF_N$, they would have to be modified as well. This project is beyond the scope of eRD17, but may be considered in the future.

On a more technical note, in developing BeAGLE, we discovered and corrected some errors in how the quenching code PyQM was integrated into DPMJetHybrid (line 14). This has not been thoroughly tested and was never considered to be a major part of eRD17 plans. We (Baker and Zheng) intend to address this in the context of the JLAB LDRD "Geometry Tagging for JLEIC" that we are participating in (see below). The authors of PyQM (Accardi & Dupre) are collaborators on that project in any case.

Finally, once we have the complete version of BeAGLE available later this fiscal year, we will address physics questions and publish a description of the program and the simulation results.

<u>What are critical issues?</u>

No major concerns have been identified.

Clearly BeAGLE needs to impart a more realistic excitation energy to the nucleus.

Additional information:

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

Baker is the only funded person on the project and he has spent about 0.07 FTE year, or half the planned budget already. This represents about 0.27 FTE x 3 months. The front-loading was built into the plan from the beginning as the BeAGLE development work needs to precede the physics simulation and paper writing.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Laboratory Physics Department funding supported the salary of Aschenauer and Lee who have primarily been working in an advisory role. Central China Normal University has supported the salary of Zheng who spends about 10% of his time on this project. BNL Physics will also support travel for Zheng to spend 3 months at BNL.

This project has begun to attract further external funding to help install BeAGLE at JLAB, integrate into their simulations, and further develop features of the program (and also Sartre) important to the JLEIC:

Specifically, Baker and Zheng joined with a group of JLAB staff and users in a successful proposal to acquire JLAB LDRD funds in a project called "Geometry Tagging for Heavy Ions at JLEIC" (2017-LDRD-6). The main thrust of this project is to implement two EIC R&D simulation programs (eRD17-BeAGLE and also RD-2012-5-Sartre) at JLAB and use them to help validate and improve the forward detector/IR design for eA collisions at a JLEIC. Vasiliy Morozov (JLAB) is the P.I. and collaborators include: A. Accardi, W. Brooks, R. Dupre, K. Hafidi, C. Hyde, P. Nadel-Turonski, K. Park, T. Toll, G. Wei, L. Zheng. This project is expected to run for two years (FY2017-2018), although only FY2017 funding is approved so far. Care has been taken so that the work done on the JLAB project and the eRD17 project don't overlap. In particular, eRD17 focuses on multinucleon shadowing and eRHIC simulations while 2017-LDRD-6 focuses on complete final state reconstruction, cold nuclear matter effects, code installation & integration at JLAB, and physics at JLEIC energies.

Publications

Please provide a list of publications coming out of the R&D effort.

N/A – as mentioned, we hope to start publishing at the end of this fiscal year.

Bibliography

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[2] A. Accardi, Phys. Rev. C76 (2007) 034902
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[4] E665 Collaboration, Z. Phys. **C65** (1995) 225